On the flat transverse momentum dependence of the single-spin asymmetry in inclusive neutral pion production

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Abstract

We discuss recent experimental results from RHIC where the flat transverse momentum dependence of a single-spin asymmetry has been found in the inclusive production of neutral pions. This dependence takes place in a wide region of the transverse momenta up to $p_T = 10$ GeV/c. We emphasize that such dependence has been predicted in the nonperturbative spin filtering mechanism for the single-spin asymmetries in hadron interactions and present some implications for this mechanism from the new experimental data.

Introduction

It should be noted that decrease with transverse momentum p_T of single–spin asymmetries (SSA) is a common feature of perturbative QCD approaches including those based on the account for the various modifications implemented into the calculation scheme originally grounded on collinear factorization. The most recent progress in this field is described in [1, 2]. The decreasing dependence has not been directly observed experimentally, but the experimental data are not very conclusive due to large statistcal errors. However, the existing experimental data are consistent with the flat transverse dependence of SSA in inclusive processes. This conclusion is valid for the old data on of Λ–hyperon polarization [3], for example, and for the most recent data obtained at RHIC [4]. It is essential that the new data cover the wide region of the transverse momentum values up to $p_T \leq 10$ GeV/c. In [6] it was noted that experimental data at higher values of p_T would be needed to perform a more conclusive test of various pQCD theoretical approaches and their predictions. The model proposed in [6] provided flat p_T -dependence of SSA. The new experimental data which have appeared very recently[4, 5] are consisnent with the observed earlier trend, i.e. flat dependence on transverse momenta can be extended to the region of higher values of p_T. Since such high values of transverse momenta have been reached experimentally, one forced to conclude that the mechanism of the SSA's generation can have a nonperturbative origin. Of course, a presence of the significant statistical errors in the current experimental data (cf. e.g [4, 5]) is the serious obstacle on the way of derivation of a completely unambiguous final conclusion on the impossibility of a decreasing dependence of the SSA with p_T.

Highlights of the filtering mechanism of SSA generation and new large-p_T experimental data

The nonperturbative QCD dynamics is closely interrelated with the two well–known phenomena, namely, color confinement and spontaneous breaking of chiral symmetry (χSB)(cf. e.g. [7]). The χSB–mechanism resulting in the transition of current into constituent quarks is directly responsible for generation of their masses and appearance of quark condensates. Constituent quarks are colored objects, they appear to be quasiparticles and a hadron is often represented as a loosely bounded system of these constituent quarks. Simultaneously, the Goldstone bosons which are the excitations of the condensates appear and mediate interactions of the constituent quarks. This interaction is mainly due to a pion field and has therefore a spin–flip nature. Filtering of the spin states results from the unitarization process in the s-channel and this mechanism connects SSA's with

asymmetries in the position (impact parameter) space [6].

The common features of SSA measurements at RHIC and Tevatron (linear increase of asymmetry with x_F and flat transverse momentum dependence at large transverse momentum, $p_T > 1$ GeV/c) are reproduced and described in the framework of the semiclassical picture based on the further development of the chiral quark model suggested in [8] and results of its utilization for the treatment of the polarized and unpolarized inclusive cross-sections. The data for unpolarized inclusive cross–sections obtained at RHIC [9] can be simultaneously reproduced.

Now we summarize the essential features of the mechanism. Valence constituent quarks are scattered simultaneously (due to strong coupling with Goldstone bosons) and in a quasi-independent way by the effective strong field. In the initial state of the reaction $pp_\uparrow \to \pi^0 X$ the proton is polarized and its wave function can be represented in the simple SU(6) model. The constituent quark $Q_\uparrow$ with transverse spin in up-direction fluctuates into Goldstone boson and another constituent quark $Q'_\downarrow$ with opposite spin direction, performing spin-flip transition [10]:

$$Q_\uparrow \to GB + Q'_\downarrow. \tag{1}$$

The π^0-fluctuations of constituent quark do not change its flavor and color. With assumption on the equal probabilities of the processes with U and D quarks:

$$U_{\uparrow,\downarrow} \to \pi^0 + U_{\downarrow,\uparrow} \quad \text{and} \quad D_{\uparrow,\downarrow} \to \pi^0 + D_{\downarrow,\uparrow}, \tag{2}$$

the production of π^0 by the polarized proton $p_\uparrow$ in this simple $SU(6)$ picture can be treated as a result of the fluctuation of the constituent quark $Q_\uparrow$ ($Q = U$ or D) in the effective field into the system $\pi^0 + Q_\downarrow$ (Fig. 1). Since total angular

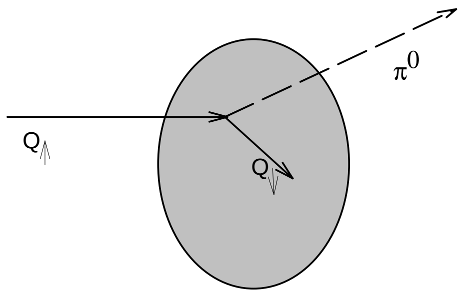

Figure 1: Chiral mechanism of π^0–production in polarized proton-proton interaction.

momentum is conserved, the compensation of quark spin flip should occur, i.e. to compensate quark spin flip $\delta\mathbf{S}$, an orbital angular momentum $\delta\mathbf{L} = -\delta\mathbf{S}$ should

be associated with the final state of reaction (1). The introduction of $\delta\mathbf{L}$ implies a shift in the impact parameter value of pion π^0:

$$\delta\mathbf{S} \Rightarrow \delta\mathbf{L} \Rightarrow \delta\tilde{\mathbf{b}}.$$

Note, that outside the hadron interior the Goldstone bosons are the usual pions and kaons. Due to different strengths of interaction at the different impact distances, i.e.

$$\begin{aligned} p_\uparrow \Rightarrow Q_\uparrow &\rightarrow \pi^0 + Q_\downarrow \Rightarrow & -\delta\tilde{\mathbf{b}}, \\ p_\downarrow \Rightarrow Q_\downarrow &\rightarrow \pi^0 + Q_\uparrow \Rightarrow & +\delta\tilde{\mathbf{b}}. \end{aligned} \tag{3}$$

the processes of transition $Q_\uparrow$ and $Q_\downarrow$ to π^0 will have different probabilities. It eventually leads to nonzero asymmetry $A_N(\pi^0)$. When the shift in impact parameter is negative, $-\delta\tilde{\mathbf{b}}$, the interaction is stronger than that with the positive shift, $+\delta\tilde{\mathbf{b}}$, and therefore the asymmetry $A_N(\pi^0)$ is positive too. The shift in $\tilde{\mathbf{b}}$ (the impact parameter of final pion) is translated to the shift of the impact parameter of the initial proton according to the relation between impact parameters in the multiparticle production:

$$\mathbf{b} = \sum_i x_i \tilde{\mathbf{b}}_i. \tag{4}$$

The essential feature of the mechanism is an account of unitarity in the direct channel of reaction. The corresponding formulas for inclusive cross–sections of the process

$$p^{\uparrow,\downarrow} + p \rightarrow \pi^0 + X,$$

have been obtained in [11]:

$$d\sigma^{\uparrow,\downarrow}/d\xi = 8\pi \int_0^\infty bdbI^{\uparrow,\downarrow}(s,b,\xi)/|1 - iU(s,b)|^2, \tag{5}$$

b is the collison impact parameter. The function $U(s,b)$ is the generalized reaction matrix (averaged over initial spin states) which is determined by the basic dynamics of the elastic scattering. The elastic scattering amplitude in the impact parameter representation $F(s,b)$ is then given [8] by the relation:

$$F(s,b) = U(s,b)/[1 - iU(s,b)]. \tag{6}$$

The equation (6) allows one to obey unitarity for the elastic scattering amplitude provided the inequality $\mathrm{Im}\, U(s,b) \geq 0$ takes place. The model [8] has been used for construction of the functional dependence of $U(s,b)$, namely, this function was chosen as a product of the factors corresponding to the averaged amplitudes

of the individual valence quarks. The strong interaction radius of the quarks is determined by its mass,

$$r_Q = \zeta/m_Q$$

The value of the parameter ζ was extracted from the experimental data for the differential cross-section of the elastic pp-scattering. In the region of medium values of t this model provides[8] the familiar Orear-type behavior:

$$\frac{d\sigma}{dt} \sim \exp\left(-\frac{2\pi\zeta}{M}\sqrt{-t}\right),$$

where M is equal to the total mass of the constituent quarks in the two colliding protons, i.e. $M = 6m_Q \simeq 2$ GeV/c, and the value of parameter $\zeta \simeq 2$ since from the experimental data $m_Q/\zeta = 150 - 200$ MeV and to reproduce the standard constituent quark masses the value of ζ should be around 2.

The functions $I^{\uparrow,\downarrow}$ in Eq. (5) can be expressed through the functions $U_n^{\uparrow,\downarrow}$ – the multiparticle analogs of the function U [11] in the polarized case. The set of the kinematical variables ξ (x_F and p_T for example) describe the state of the produced pion.

We can connect $\delta\tilde{b}$ with the radius of quark interaction r_Q^{flip} responsible for the transition changing quark spin:

$$\delta\tilde{b} \simeq r_Q^{flip}.$$

With above relation the following expression for asymmetry $A_N^{\pi^0}$ can be written

$$A_N^{\pi^0}(s,\xi) \simeq -x_F r_Q^{flip}\frac{1}{3}\frac{\int_0^\infty bdbI_0'(s,b,\xi)db/|1-iU(s,b)|^2}{\int_0^\infty bdbI_0(s,b,\xi)/|1-iU(s,b)|^2}, \quad (7)$$

where $I_0'(s,b,\xi) = dI_0(s,b,\xi)/db$. It is evident that $A_N^{\pi^0}(s,\xi)$ should be positive because $I_0'(s,b,\xi) < 0$. In this model (details can be found in [6]) the energy and p_T-independent behavior of asymmetry $A_N^{\pi^0}$ takes place at the large values of transverse momentum $p_T \gg x_F/R(s)$:

$$A_N^{\pi^0}(s,x_F,p_T) \sim x_F r_Q^{flip}\frac{M}{3\zeta}. \quad (8)$$

This flat transverse momentum dependence of the asymmetry is due to the similarity of the rescattering effects affecting different spin states. Namely, the spin-flip and nonflip interactions are affected by absorption at short distances in a similar way and the relative magnitude of the absorption does not depend on energy. It is the result of the unitarization. The numerical value of polarization $A_N^{\pi^0}$ can be significant. Indeed, there is no small factor in (8). The function $R(s)$ is the

hadron interaction radius ($R(s) \sim \ln s$), the typical numerical falue of R has been taken to be equal to 1 fm. Thus, the typical value of $x_F/R(s)$ is 0.1 GeV/c and the Eq. (8) which is valid at $p_T \gg x_F/R(s)$, should be applicable in the region $p_T > 1$ GeV/c. The value of r_Q^{flip} is of order $\sim 10^{-1}$ fm on the basis of the model estimates [6, 8, 11]. The radius of quark interaction r_Q^{flip} responsible for the transition $Q_\uparrow \to Q_\downarrow$ changing quark spin. The production of π^0 is considered in the fragmentation region, i.e. at large x_F and the approximate relation

$$b \simeq x_F \tilde{b}, \tag{9}$$

which results from Eq. (4) has been used with additional assumption on the small values of Feynman x_F for the other particles. The linear increase of asymmetry with x_F follows from the above considerations which, of course, are approximate and valid at x_F around unity. Therefore, at smaller values of x_F the linear dependence is distorted.

Thus, Eq. (8 valid in the region of large x_F. The flat dependence of asymmetry on p_T provided by this relation is consistent with the new data from RHIC (we have used data available at the largest values of x_F due to approximation made in the model and discussed above) [4, 5] (cf. Fig. 2,3). Comparison with the

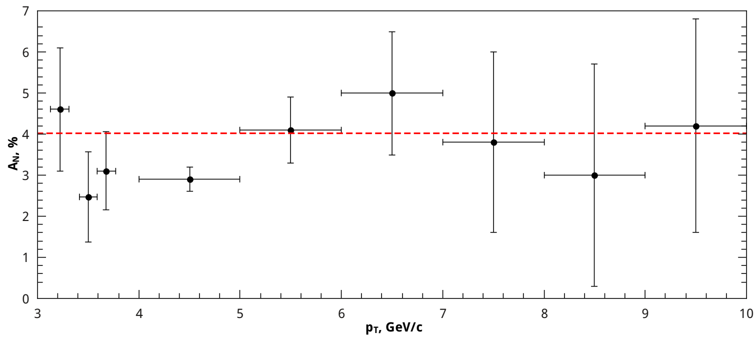

Figure 2: p_T -dependence of the asymmetry A_N in the process $p_\uparrow + p \to \pi^0 + X$ at RHIC, preliminary data from [4, 5] correspond to pion isolation of 70 mR, $\sqrt{s} = 500$ GeV and $0.32 < x_F < 0.40$.

data allows one to estimate the value of r_Q^{flip} more precisely , namely $r_Q^{flip} \simeq 0.05$ fm. Similar mechanism generates SSA in the inclusive production of charged pions. It should be noted that dependencies of SSA on p_T consistent with the flat ones have also been observed at lower values of x_F, namely, in the two regions $0.16 < x_F < 0.24$ and $0.24 < x_F < 0.32$ [4, 5]. The data demonstrate increase of SSA with x_F. Due to limitation of the model for the large x_F region, we have not used those data, but, in principle, the model is in agreement with them too.

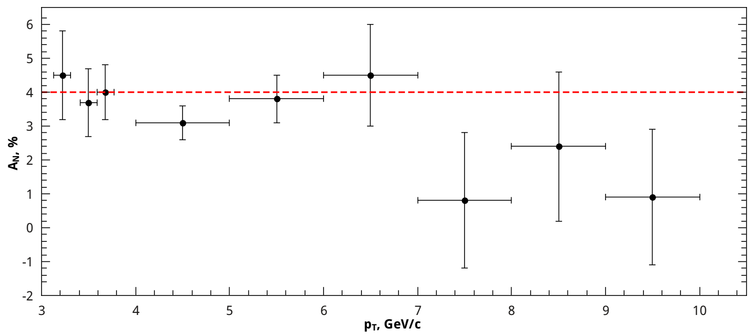

Figure 3: The same plot as in Fig.2, but with data corresponding to pion isolation of 30 mR.

The mechanism of chiral quark fluctuation in the effective field with spin flip is suppressed compared to the direct elastic scattering of quarks and, therefore, it does not play a role e.g. in the reaction $pp_\uparrow \to pX$ in the fragmentation region, but it is not the case for the reaction $pp_\uparrow \to nX$. The above features can be observed experimentally: asymmetry A_N is consistent with zero for proton production and significantly deviates from zero for neutron production in the forward region.

In the paper [14] an important issue has been raised, namely a model when trying to explain spin asymmetries should simultaneously describe data for the unpolarized inclusive cross-sections. In this approach with effective degrees of freedom – constituent quarks and Goldstone bosons – unpolarized inclusive cross–section at high transverse momenta has a generic power-like dependencies on p_T . At high p_T the power-like dependence p_T^{-n} with $n = 6$ takes place. It originates from the singularity at zero impact parameter $b = 0$. The exponent n does not depend on x_F. This p_T^{-6}–dependence of the unpolarized inclusive cross–section can in principle describe the respective experimental data (Fig. 4) [6].

Conclusion

It was shown that prediction of the spin filtering mechanism [6] on the flat p_T-dependence of single-spin asymmetries is consistent with the new experimental data from RHIC. As it often happens, this interpretation is not unique. Such flat dependence can result from finite size of a constituent quark and a presence of the orbital angular momentum of the current quarks residing inside the constituent one [12, 13]. This mechanism is based on the similar ideas as the spin filtering one but is, in principle, different and has no predictive power for x_F dependence of SSA. Thus, we would like to treat the seemingly flat p_T-dependence of SSA

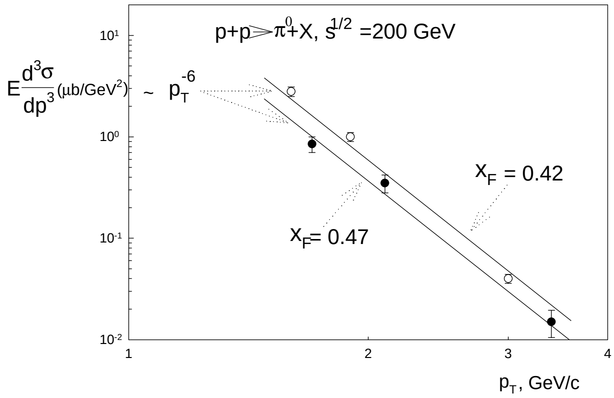

Figure 4: Transverse momentum dependence of unpolarized inclusive cross–section, experimental data from [9].

in favor of the spin filtering mechanism, while the presence of the internal orbital momentum in the structure of constituent quarks still remains to be an interesting option and cannot be excluded at the moment (cf. e.g. [15]).

Finally, we would like to stress again that the experimental data set [4, 5] is the preliminary one and we hope that the final set of data will have smaller statististical error bars and allow one to provide quantitative discriminitions of model predictions for SSA.

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References

[1] Y.V. Kovchegov, M.D. Sievert, Phys. Rev. D 86 (2012) 034028.

[2] A. Metz, D. Pitonyak, arXiv:1212.5037v1, 2012.

[3] L. Pondrom, Phys. Rep. 122 (1985) 57.

[4] S. Heppelmann (for STAR Collaboration), Talk at 2012 RHIC and AGS Annual Users' Meeting, BNL, Upton, June 12-15, 2012.

[5] G. Igo, Talk at the Interanational Workshop on Diffraction in High Energy Physics (Diffraction 2012), Puerto del Carmen, Lanzarote, Canary Islands, Spain, September 10-15, 2012.

[6] S.M. Troshin, N.E. Tyurin, Phys. Part. Nucl. 41 (2010) 54.

[7] H. Georgi, A. Manohar, Nucl. Phys. B 234 (1984) 189.

[8] S.M. Troshin, N.E. Tyurin, Phys. Rev. D 49 (1994) 4427.

[9] J. Adams et al.(STAR Collaboration), Phys. Rev. Lett. 92 (2004) 171801.

[10] T.P. Cheng, L.F. Li, Phys. Rev. Lett. 80 (1998) 2789.

[11] S.M. Troshin, N.E. Tyurin, Z. Phys. C 45 (1989) 171.

[12] S.M. Troshin, N.E. Tyurin, Phys. Rev. D 52 (1995) 3862.

[13] V.V. Mochalov, S.M. Troshin, A.N. Vasiliev, Phys. Rev. D69 (2004) 077503.

[14] C. Bourrely, J. Soffer, Eur. Phys. J. C 36 (2004) 371.

[15] F. Arash, Talk at the Interanational Workshop on Diffraction in High Energy Physics (Diffraction 2012), Puerto del Carmen, Lanzarote, Canary Islands, Spain, September 10-15, 2012.